Validating the use of satellite SAR for measuring small-scale surface wind variations

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Abstract-

Unique low-level aircraft measurements of air-sea coupling, coincident with a RADARSAT SAR ocean image, are presented. This study provides quantitative evidence to support the hypothesis that the satellite synthetic aperture radar (SAR) can be used to detect and monitor microscale air-sea coupling. The SAR image (at right) suggests wide-spread atmospheric boundary layer roll impacts on the sea surface, having horizontal length scales of 1-3 km, that are most likely associated with local wind modulation. This north-to-south streaking on the SAR image is supposedly the ocean surface wave analog to commonly observed "cloud streets" or "wind rows" that often ride atop the atmospheric boundary layer. Air motion and radar-derived sea surface roughness data from the NOAA Long-EZ aircraft show, via direct covariance, that the main cause of surface wave modulation is the wind speed variation - consistent with a first-order helical roll vortex model. Further studies to explain secondary features within the multi-dimensional process are ongoing.

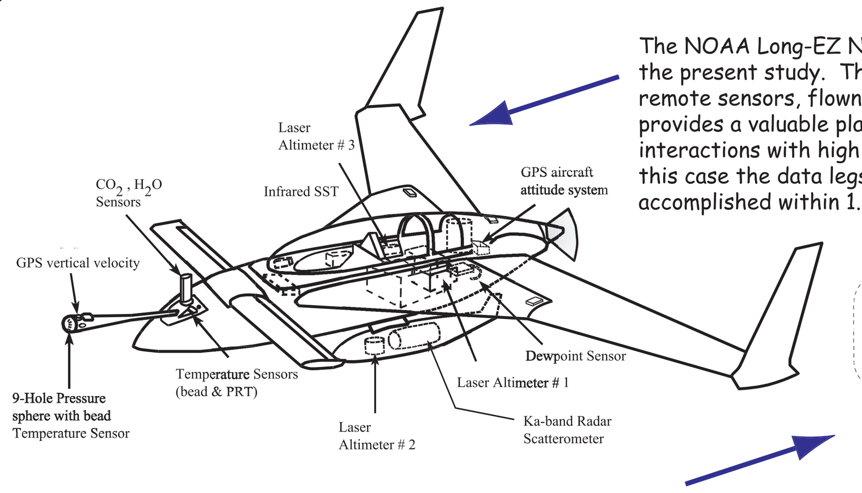
Background and objectives

Global climate models are evolving to capture finer and finer spatial and temporal scales for processes such as the flux of mass, momentum and heat between the ocean and atmosphere. Ocean remote sensing plays an important role in this evolution by providing global oceanic observations and one of these products is the near-surface wind speed (e.g. from QuikScat). At this point, scales of ocean-atmosphere interaction below 50-100 km are often considered as sub-grid variability that is too complex and/or unknown for inclusion. The present aircraft study was initiated to assess the use of high-resolution ocean radar backscatter images to gain new insight on the scales of air-sea interaction that take place inside of the typical 10-50 km^2 footprint of wind sensors such as the scatterometer or radiometer.

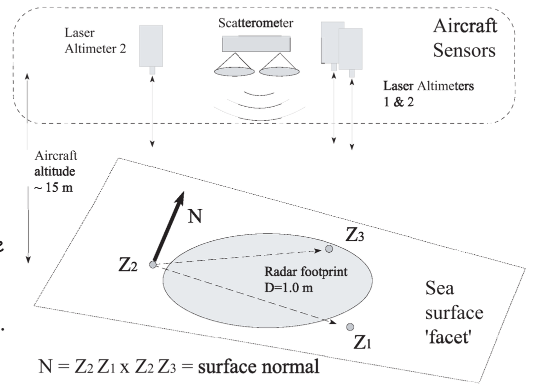
It has long been suggested (e.g. see Brown, 1991) that ocean surface backscatter images from the SAR can serve a purpose in developing beter models for marine atmospheric boundary layer (MABL) turbulence. Processes such as organized large eddies are ubiquitous within the MABL and the inherent SAR's 10-100 m spatial resolution is more than adequate to sample surface impacts at these eddy scales more or less instantaneously. One key unresolved issue in this objective has been in situ validation confirming that coherent image features are indeed the surface (i.e. short ocean wave) response to corresponding atmospheric eddies within the MABL. The difficulty of such space/time validation is apparent. Here, as one attempt, we present aircraft measurements of near-surface atmospheric boundary layer roll signatures and radar-derived sea surface roughness taken coincident with a RADARSAT SAR image. The following data provide an overview of the field experiment, SAR image analysis, and aircraft data in support of this objective.

Field experiment- NOAA LongEZ under the RADARSAT SAR

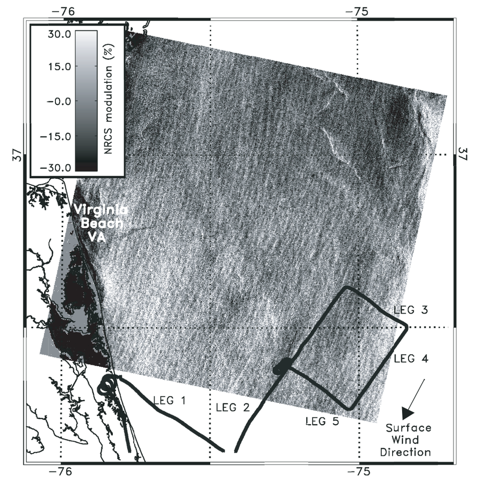
This case study was conducted on 5 Nov. 1997 during a pilot program for the Office of Naval Research's Shoaling Wave Experiment (SHOWEX). The aircraft flight was timed to coincide with the passing of the RADARSAT SAR. Most fortunately, the data collection coincided with a mild cold air outbreak that led to an organized secondary atmospheric flow within the MABL. Figures below describe the conditions and basic data collection.



The NOAA Long-EZ N3R aircraft including all sensors relevant to the present study. The combination of high rate flux and surface remote sensors, flown at an altitude of 15-25 m above the ocean, provides a valuable platform for extensive spatial sampling of air-sea interactions with high fidelity and m-scale horizontal resolution. In this case the data legs on the flight map (see the SAR image) were accomplished within 1.5 hours.



A sketch of the aircraft's sea surface measurement sensors and their surface geometry. A Ka-band scatterometer points directly down to a 1 m patch encompassed by laser altimeter estimates. The lasers measure the wave elevation, range-to-surface and 2D slope of the patch illuminated by the radar. Together, both long and short-wave slope variances can be assessed along the flight track.



Map of the experiment region off the coast of North Carolina including the RADARSAT SAR image. SAR image intensity is shown as local modulation of the normalized radar cross section. Streaks running from NE-to-SE are the features under study here. The flight tracks of the NOAA research aircraft are superimposed as is the aircraftís measurement of wind direction. Data were collected on 5 November 1997 and the aircraft flight occurred within one hour of the SAR overpass, 0510 local time.

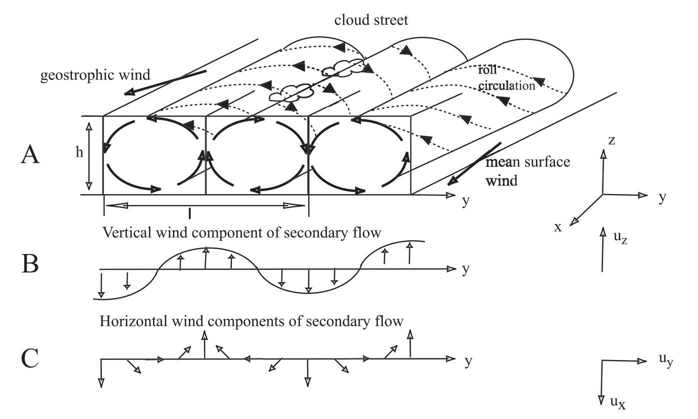
Photo of the cloud patterns (streets) observed from the NC shoreline at SAR overpass time. The visual data suggested north-to-south orientation and aircraft profiles confirmed the clouds resided at the boundary layer inversion occurring at about 1.1 km. Above this level the wind direction was roughly orthogonal to the boundary layer flow indicating strong shear.

Near-surface data measured from the aircraft give the mean surface wind speed to be 7.5 m/s from 40^{o} N, wave height = 1.8 m, z/L = -0.3, air-sea temperature = -5^{o} C, and total heat flux = 170 Wm^{-2}. These conditions are consistent with a mild cold-air outbreak.

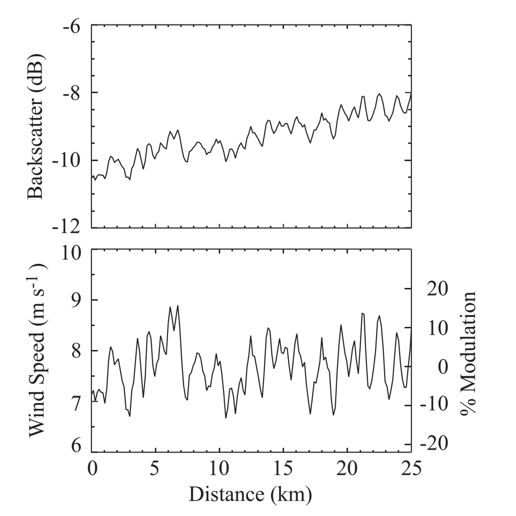
SAR image analysis - boundary layer impacts ?

The general north-to-south streaking apparent in Figure 3 is nearly aligned to the near-surface wind direction and consistent with an organized secondary flow as described by Brown (1991). In Mourad et al. (2000) the spatial structure within image this SAR image is investigated (see below) to show:

- a dominant cross-wind (i.e. cross-roll) modulation scale of 1.5-3 km
- a cross-to-alongwind modulation aspect ratio of 3:1
- S-wind speed modulations (at the 1.5 km scale) of about 0.9 m/s
- substantial sub-structure consistent with an multi-dimensional eddy field



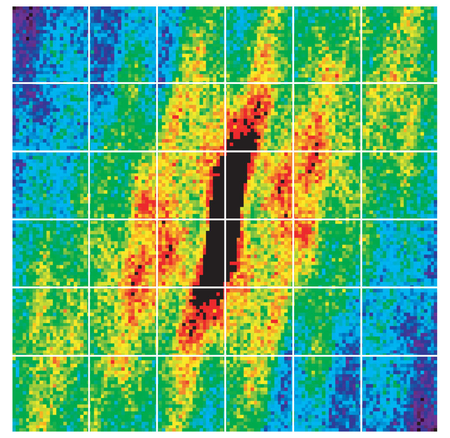
Idealized diagram of an atmospheric helical roll vortex field (from Alpers and Brummers, 1994). The first-order features: general along-wind organization of the roll structures created and/or maintained by shear aloft; regions of near-surface convergence and divergence are associated with increased or decreased wind speeds and modulated wind direction; similarly clouds form at the cap; the turbulent eddies generally scale with the boundary layer height; the process is 3 dimensional and intermittent.



"Across-roll" radar cross section data extracted from the RADARSAT SAR image near data leg 3. (top) Radar cross section versus distance. (bottom) SAR wind speed derived from NRCS data as described in Mourad et al. (2000). Note the obvious modulations at 1-5 km length scales.

Autocorrelation computed for the 25 km square SE corner of the SAR image at left. Structure in both x and y is evident and consistent with the predicted surface impacts: streaking aligned near to the wind direction, cross-roll scales of 1-3 km, along-to-cross roll aspect ratio of 3:1, substantial substructure related to the multi-scale near-surface impacts.

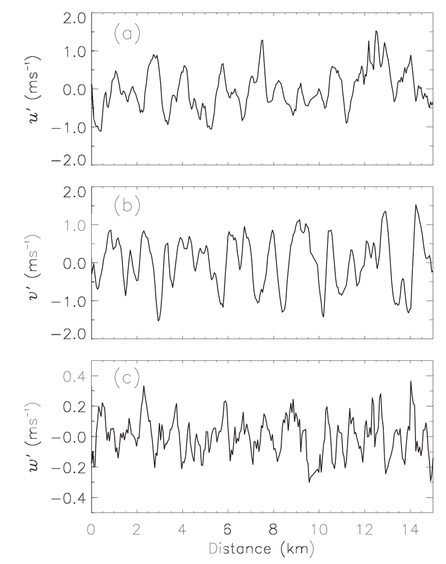
Note that this fairly coherent structure resides within the nominal 25 km square scatterometer wind vector cell.



Aircraft Validation - direct air and sea measurements

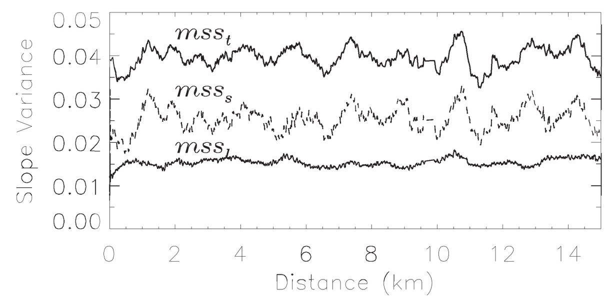
The aircraft's 15 m flight altitude permits direct measurement of horizontal and vertical air motions within the surface flux layer, coincident aircraft radar-derived surface roughness measurements. The LongEZ flew transects (see SAR image) both across and along the near-surface wind (and roll vortex) direction. Prior to these legs the aircraft provided vertical profiling data to document the PBL height and shear aloft. One notable point is that these transect data represent a very narrow (< 1 m, surface or air) spatial slice through the eddy field - making the fidelity of the observations quite remarkable. These measurements and their analysis are described in Vandemark et al. (2001) and summarized below. The most fundamental findings related to eddy field signatures:

- a dominant cross-wind (i.e. cross-roll) wind speed modulation scale of 1.5-2 km; spectral signatures consistent with the SAR
- wind speed modulations (at the eddy scale) of 1.0 m/s
- wind direction modulations (at the eddy scale) of 30 deg.
- radar-inferred wind speed modulations (at the eddy scale) of about 0.9 m/s
- consistently high cross-correlation between the wind speed and radar-derived surface roughness modulations, values for R as high as 0.7 .
- much weaker correlation between surface roughness and wind direction or vertical velocity component modulations
- best air-sea correlation for shortest waves, weaker for the intermediate scale waves



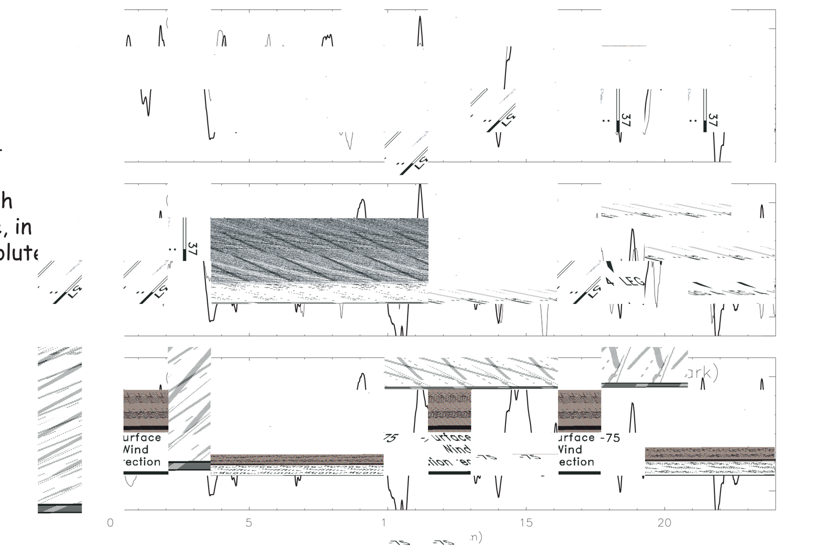
As mentioned, the LongEZ-derived winds had a mean speed of 7.5 m/s and direction=40^{o} N. Here we show the variance of wind components for 15 km of the cross-roll flight leg #3. (a) Fluctuation of the measured alongwind (b) crosswind and (c) vertical wind velocity. The modulation of signals at scales of 1-2 km is obvious in both u' and v', while the scales are shorter for the vertical fluctuations. The measured phase between u' and v' is 90 deg. in accord with the roll vortex sketch at left.

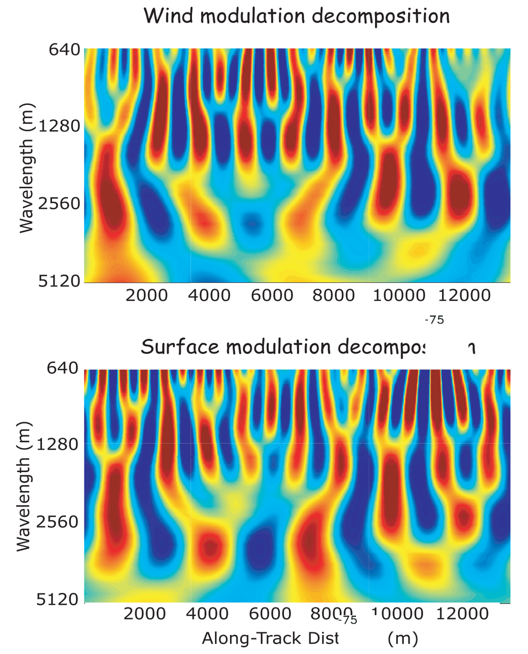
Long-EZ derived mean square slope (mss) data measured along this same flight leg 3. These multi-scale data come from the radar (total mss=mss_t), lasers (long wave mss=mss_l) and simple subtraction of the two (short-wave mss_s = mss_t - mss_l). The most pronounced modulations in the data occur for mss_s while the long wave (actually 1-5 m waves) variance shows weaker fluctuations.



(a) Direct comparison of fluctuation in the short-scale slope term, mss_s', with the wind velocity component u'[dark trace], (b) with w' , and (c) with changes in wind direction. Wind direction change, in degrees, is presented as the negative of the absolute value. Data were collected along flight leg 2, an alongwind leg.

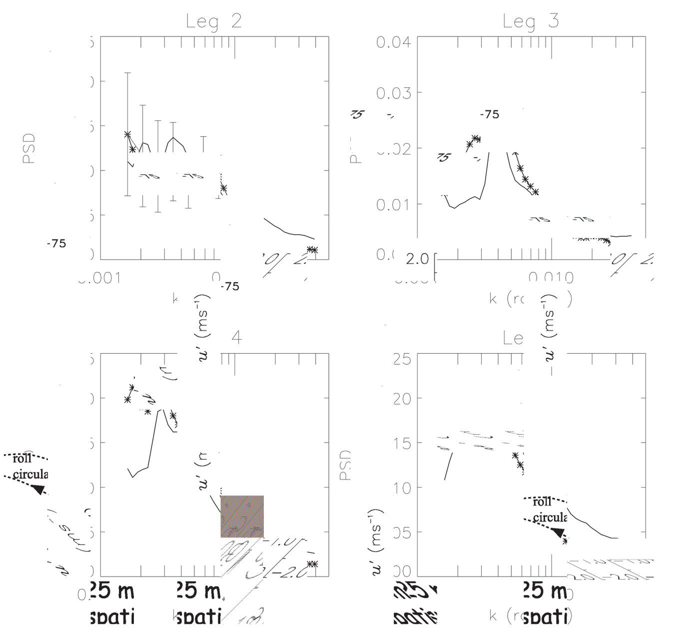
Striking agreement is evident between the wind speed and slope variance while correlatiion is weak, at best, in the lower panels.





We performed a continuous wavelet decomposition of the air and sea signals to illustrate and isolate the coherence versus various spatial scales running from 400 to 4000m. The two images here provide a striking picture of the degree of similarity between the wind and resulting surface response. (top) Image of the real coefficients from the continuous wavelet transform of u' and (bottom) mss_s' for data collected along flight leg 3. Image intensity is displayed with a linear color table having equal normalization for both the top and bottom images, thus they are directly comparable.

The close agreement of these images at various length scales indicates the close coupling between air forcing and wave generation associated with the MABL eddy field.



Power spectral density derived from the Morlet wavelet analysis as a function of wavenumber for the noted four flight legs . The solid trace represents the spectral density for the alongwind data, u' , while the trace with symbols is for slope variance, mss_s'. Estimate uncertainty for the spectra are provided in the upper left plot.

References:

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